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For the Period:

April 1, 1997 through March 31, 2000

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(1) High Speed (THz) Nonlinear Optical Effects in Semiconductor Amplifiers-New Effects and Devices
(2) Transient Dynamics of Cavity Formation in Laser Diodes
(3) New Nonlinear Materials for Optical Frequency Conversion
(4) Integration of Diffractive Optics with Smart Pixels for Optical Communications, Networking and Computing
(5) Ultra-High Capacity Tb/s Optical Switching Using a Nonlinear Optical Loop Mirror with Time and Wavelength Selectivity

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JOINT SERVICES ELECTRONIC PROGRAM

"RESEARCH IN ELECTRONICS"

OE1-1 W. Steier

HIGH SPEED (THz) NONLINEAR OPTICAL EFFECTS IN SEMICONDUCTOR AMPLIFIERS - NEW EFFECTS AND DEVICES

OE1-2 A. Levi

TRANSIENT DYNAMICS OF CAVITY FORMATION IN LASER DIODIES

OE1-3 J. Feinberg

NEW NONLINEAR MATERIALS FOR OPTICAL FREQUENCY CONVERSION

OE 1-4 A. Sawchuk

INTEGRATION OF DIFFRACTIVE OPTICS WITH SMART PIXELS FOR OPTICAL COMMUNICATIONS, NETWORKING AND COMPUTING

OE 1-5 A. E. Willner

ULTRA-HIGH-CAPACITY Tb/s OPTICAL SWITICHING USING
A NONLINEAR OPTICAL
LOOP MIRROR WITH TIME AND WAVE LENGTH SELECTIVITY

High Speed (THz) Nonlinear Optical Effects in Semiconductor Amplifiers- New effects and Devices

Johan P. Burger, Serge Dubovitsky, William H. Steier

OE1

Demonstration of Filter Free Wavelength Conversion Using Four-Wave-Mixing in a Semiconductor Optical Amplifier

We demonstrated, for the first time, a completely filter-free FWM wavelength conversion in broad-area semiconductor optical amplifiers. The non-collinear four-wave mixing configuration makes it possible to separate the output converted signal from the straight-through converter beam without using narrow-band optical filters. In a conventional FWM wavelength conversion, the signal, pump, and/or converter beams are collinear. The wavelength shifted signal appears as a sideband on the converter beam which cannot be resolved from the original signal except by the use of an optical bandpass filter. The use of the non-collinear configuration makes it possible to spatially separate the converted signal from the straight-through converter beam without using a narrow-band optical filter. Furthermore, by using a mixed-strain multiple quantum well (MQW) amplifier, the converted signal can be further isolated from the strong pump beam, resulting in a completely filter-free operation.

The non-collinear FWM configuration provided a 29dB isolation between the converted signal and the straight-through converter beam. We also obtained a 4.9dB conversion efficiency, a wide 3-dB efficiency bandwidth of 40nm and a high signal-to-noise ratio of 28dB. Further suppression of the strong pump beam from the converted signal was realized by using a mixed strain MQW amplifier. A pump beam isolation of 19.2dB from the converted signal was achieved.

Nonlinear Optics in a Dual Moded Waveguide Semiconductor Optical Amplifier

We completed a study of nonlinear optical interactions in dual moded waveguides. For efficient NLO interactions it is important to use a geometry which allows for complete separation of the NLO mixing products based either on wavelength, direction of propagation, or waveguide mode. In our earlier work we showed how these mixing products could be separated based on direction of propagation in a broad area SOA. Based on this work, we have developed a practical integrated optics geometry, in a dual molded waveguide, which enables efficient nonlinear interactions *and* easy separability of the interacting

waves and any mixing products. We have shown how this approach can be used to implement tunable narrowband notch filtering, optical carrier suppression, and all optical wavelength sensitive switching and tapping.

As one example of the simulation results we show the power transfer due to TWM between a signal and control beam propagating in a two moded SOA waveguide structure with a central lateral heterojunction , as a function of detuning. The material and waveguide parameters used were appropriate for a strained MQW InGaAsP structure at the 1.32μm wavelength. The material parameters used were previously measured for a broad area device[4]. In this device the signal wave can be suppressed more than 30dB in a narrow frequency band above the control wave frequency, while no sidebands are generated. This is attractive for rapidly tunable all-optical notch filtering as well as optical carrier suppression in RF photonics.

Publications

1. "Ambipolar diffusion coefficient and carrier lifetime in a compressively strained InGaAsP multiple quantum well device", D. Zhu, S. Dubovitsky, W. H. Steier, J. Burger, K. Uppal, D. Tishinin, P. D. Dapkus, Appl. Phys. Lett., Aug. 4, 1997
2. "Filter free wavelength conversion based on non-colinear four wave mixing in a semiconductor optical amplifier" D. X. Zhu, S. Dubovitsky, W. H. Steier, K. Uppal, D. Tishinin, P. D. Dapkus. J. Burger; Paper CWC6, CLEO, May 1997.
3. "An all-optical wavelength decoding switch based on four wave mixing in a semiconductor optical amplifier" D. X. Zhu, S. Dubovitsky, W. H. Steier, D. Tishinin, K. Uppal, P. D. Dapkus, J. Berger, S. Garner, OSA Topical Meeting on Optical Amplifiers and their Applications, Paper TuD8-1, Victoria, B. C. Canada, 1997
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5. "Design and fabrication of semiconductor optical amplifiers for all-optical switching", D. X. Zhu, S. Dubovitsky, W. H,. Steier, D. Tishinin, P. D. Dapkus, K. Uppal, *ICAPT '98*, Ottawa, Canada.
6. "Linewidth enhancement factor in broad area semiconductor optical amplifiers", D. X. Zhu, S. Dubovitsky, W. H,. Steier, D. Tishinin, P. D. Dapkus, K. Uppal, *ICAPT '98*, Ottawa, Canada.

7. "Multiple Wavelength Conversion by Nearly Degenerate Four-Wave Mixing in Semiconductor Optical Amplifier", D. X. Zhu, S. Dubovitsky, W. H. Steier, K. Uppal, P. D. Dapkus. OFC, Dallas,1997.

8. "Nonlinear Optics in a Dual Moded Waveguide Semiconductor Optical Amplifier", Johan P. Burger, Serge Dubovitsky, William H. Steier, LEOS '98, Decermber, 1998, Orlando, FL.

Graduated Students

Daniel. X. Zhu, Ph. D. in Electrical Engineering

Transient Dynamics of Cavity Formation in Laser Diodes

A. F. J. Levi

OE-2

We have worked to develop a basic understanding of the principles of operation of novel photonic devices. We anticipate that such devices will be needed in future, significantly more complex, photonic systems. With a view towards such next-generation components, we have focused our research on (i) improving the design and performance of microdisk lasers, (ii) studying the noise performance of ultra-small devices and, (iii) using hybrid macroscopic semiconductor laser cavities to explore the underlying physics of multi-state logic devices.

Conventional microdisk lasers, by virtue of their geometry, suffer from poor thermal characteristics which has limited continuous operation to cryogenic temperatures. To improve the thermal design without significantly degrading the optical confinement in an optically pumped microdisk laser, the active region should be in intimate contact with a material of high thermal conductivity, low refractive index and low optical loss. We have achieved this by wafer-bonding InGaAs/InGaAsP/InP semiconductor active region to sapphire. Using this technique, we have experimentally demonstrated continuous room-temperature lasing operation with a threshold pump power of 1.1 mW for a 4.5 μm diameter disk with a lasing wavelength of 1.55 μm (Ref. 1). To control the lasing wavelength of these devices we have developed a post-processing technique in which a thin SiO_2 over-layer is deposited on the laser. Using this method we have shown that emission wavelength can be tuned up to 8 nm for a 3 μm diameter disk (Ref. 2).

We have also successfully designed and demonstrated continuous room-temperature operation of microdisk laser diodes using aluminum oxide technology. In these devices, the active region near the periphery is encased in low-refractive index aluminum oxide, thereby providing significant optical confinement and enhanced thermal management. This has led to the realization of continuous room-temperature lasing operation with a threshold current of 2.25 mA for a 17 μm diameter disk with a lasing wavelength of 1.0 μm (Ref. 3). Suppressing carrier injection in the middle of the disk will reduce the overall threshold current of the laser since the whispering gallery resonance (and lasing action) is strongly confined to the periphery of the disk. Using an improved electrical design with insulating current blocking layer near the middle of the disk, we have obtained continuous lasing operation with a threshold current of 1.2 mA for a 9.5 μm diameter disk with a lasing wavelength of 1.0 μm (Ref. 4).

The noise performance of scaled lasers with very small active and cavity volumes has been investigated. Understanding the noise behavior of small laser devices is important as we anticipate future photonic systems will make use of many small laser components. Our work showed how relative intensity noise in small lasers depends critically on the type of pump (thermal bath) used to drive the laser (Ref. 5). Our studies of scaled lasers also showed the existence of an optimal region for spontaneous emission factor, β, for high-speed digital modulation was identified (Ref. 6).

Methods to switch lasing wavelengths (Ref. 7) in a multi-cavity laser was explored experimentally (Ref. 7). Multiple stable lasing states have also been observed. We expect that such components can be exploited to make photonic logic devices and can be used to further expand the signal bandwidth of high-speed data transmission (Refs. 8 - 10).

List of JSEP publications:

(1) Continuous room-temperature operation of optically pumped InGaAs/InGaAsP microdisk lasers, S. M. K. Thiyagarajan, A. F. J. Levi, C. K. Lin, I. Kim, P. D. Dapkus, and S. J. Pearton, Electronics Lett. **34**, 2333-2334 (1998).
(2) Active microdisk devices, S. M. K. Thiyagarajan and A. F. J. Levi, SPIE's symposium on Integrated optoelectronics – In-plane semiconductor lasers IV, San Jose, CA, Jan 2000.
(3) Continuous room-temperature operation of microcylinder laser diodes, S. M. K. Thiyagarajan, D. A. Cohen, A. F. J. Levi, S. Ryu, R. Li, and P. D. Dapkus, Proceedings of ECIO '99, 9^{th} European Conference on Integrated Optics and Technical Exhibition, Torino, Italy, April 13-16 1999, 327-330 (1999).
(4) Continuous room-temperature operation of microdisk laser diodes, S. M. K. Thiyagarajan, D. A. Cohen, A. F. J. Levi, S. Ryu, R. Li, and P. D. Dapkus, Electronics Lett. **35**, 1252-1254 (1999).
(5) Noise in voltage-biased scaled semiconductor laser diodes, S. M. K. Thiyagarajan and A. F. J. Levi, Solid State Electronics, **43**, 33-39 (1999).
(6) Signal quality in digitally modulated scaled laser diodes, S. M. K. Thiyagarajan and A. F. J. Levi, Solid State Electronics, **42**, 2027-2030 (1998).
(7) Wavelength switching in multi-cavity laser diodes, S. M. K. Thiyagarajan, A. P. Kanjamala and A. F. J. Levi, J. Appl. Phys., **84** (4), 1805-1812 (1998).
(8) A multi-state external cavity laser diode, A. P. Kanjamala and A. F. J. Levi, Appl. Phys. Lett., **72** (18), 2214-2216 (1998).
(9) Wavelength selective electro-optic flip-flop, A. P. Kanjamala and A. F. J. Levi, Electronics. Lett., **34**, 299-300 (1998).
(10) Wavelength selection for Gigabits-per-second data transmission using out-of-band RF modulation, A. P. Kanjamala and A. F. J. Levi, IEEE Photonics Tech. Lett., **9**, 1265-1267 (1997).

JSEP-supported student who has graduated:
A. P. Kanjamala, Ph. D. in Electrical Engineering granted by USC May 1998. He is currently employed at SDL Inc., San Jose, CA.

New Nonlinear Materials for Optical Frequency Conversion

J Feinberg

OE-3

This project is to understand, enhance, and control the optical response of silica glass, especially the Ge-doped glasses used in optical communication fibers. We previously studied the ability of such glasses to perform second-harmonic generation. Here we studied the ability of UV light to permanently alter the refractive index of such glasses.

Germanium doping increases the refractive index of the fiber's core to enable it to guide light. An unexpected advantage of using Ge is that it makes the fiber's core sensitive to UV light. By shining a pattern of UV light transverse to the fiber, a refractive index grating can be permanently impressed into the fiber core. Such gratings are used in WDM communication systems to route individual channels.

We studied the dependence of fiber photosensitivity on the concentration of Ge atoms, on the presence of hydrogen in the glass, and on the wavelength of the incident ultraviolet light. We also performed experiments to understand the temperature stability of gratings written in germanium-doped silicate glass fibers with no hydrogen loading. We impressed both Bragg and long-period gratings into the core of such fibers by illuminating from the side with patterned ultraviolet light.

A known method to increase the photosensitivity of glass is to soak the glass in high-pressure hydrogen. The hydrogen molecules diffuse through the glass fiber and into its Ge-doped core. Exposing the fiber to UV light then causes a large index change in the fiber core. However, hydrogen loading of fibers is a time-consuming process. Additionally, hydrogen loading causes the formation of hydroxyl bonds. These bonds have undesirable overtone absorption at 1.4 microns, adjacent to the communications band at 1.55 microns.

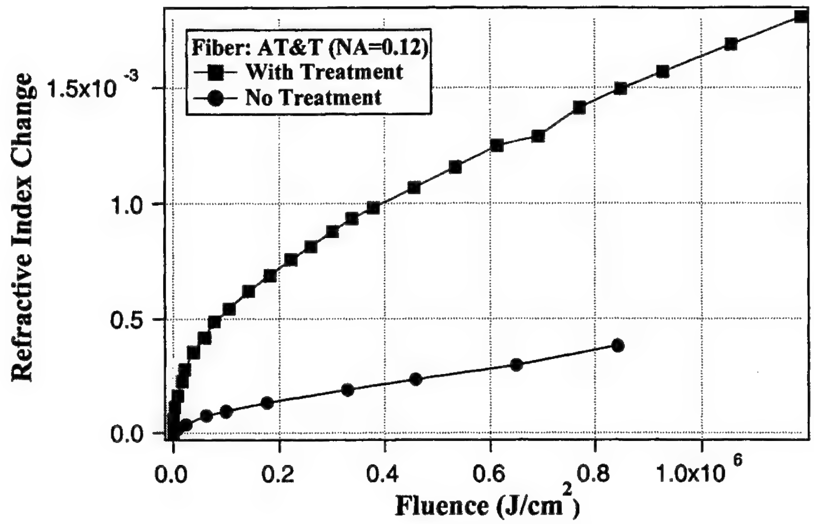

Fig. 1. Straining an optical fiber by 3% while exposing it to UV light increases both the saturated refractive index change and the rate of grating formation.

We invented an alternate method to increase the photosensitivity of un-hydrogenated Ge-doped glass fibers. We discovered that putting the fiber under strain increases the photosensitivity of the glass, in some fibers by more than an order of magnitude. Fig. 1 shows that in the stretched fiber (AT&T telecom fiber) the refractive index grew more quickly (by a factor of 20) and saturated at a larger value compared to the unstretched fiber.

JSEP publications:

Journals:

1) "Photochemical reaction of hydrogen with germanosilicate glass initiated by 3.4 – 5.4 eV ultraviolet light," V. Grubsky, D. S. Starodubov, and J. Feinberg, **Optics Letters** 24, 729-731 (1999).

2) "Increase of photosensitivity in Ge-doped fibers under strain," E. Salik, D. S. Starodubov, and J. Feinberg, submitted 23 Mar 2000 to **Optics Letters.**

Conference Proceedings:

3) "Increase of photosensitivity in Ge-doped fibers under strain," E. Salik, D. S. Starodubov, V. Grubsky, and J. Feinberg, OFC-2000, Baltimore, Maryland, March (2000).

4) "The role of oxygen deficient centers in hydrogen-loaded germanosilicate glass," D. S. Starodubov, V. Grubsky, M. Ewart, J. Feinberg, E. M. Dianov, A. A. Rybaltovskii, and A. O. Rybaltovskii," OSA Topical Meeting on Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides, Stuart, Florida, September 23-25 (1999).

5) "Thermally stable gratings in optical fibers without temperature annealing," E. Salik, D. S. Starodubov, V. Grubsky, and J. Feinberg, Optical Fiber Communication Conference OFC'99, San Diego, California February 21-26 (1999).

6) "Effect of molecular water on thermal stability of gratings in hydrogen-loaded optical fibers," V. Grubsky, J. Feinberg, and D. S. Starodubov, Optical Fiber Communication Conference OFC'99, San Diego, California February 21-26 (1999).

7) "Explanation of strong UV-induced index change in hydrogen-loaded germanosilicate fibers," V. Grubsky, D. S. Starodubov, A. Skorucak, and J. Feinberg, Annual Meeting of the Optical Society of America, Baltimore, Maryland, October 4-9 (1998).

8) "Mechanisms of index change induced by near-UV light in hydrogen-loaded fibers," V. Grubsky, D. S. Starodubov, and J. Feinberg, Bragg Gratings, Photosensitivity and Poling in Glass Fibers and Waveguides: Applications and Fundamentals, in Williamsburg, Virginia, Oct 26-28, 1997.

Students supported by JSEP:

Ertan Salik, completing thesis

Victor Grubsky, Ph. D. Physics, 1999

Integration of Diffractive Optics with Smart Pixels for Optical Communications, Networking and Computing

Alexander A. Sawchuk
OE-4

Research Objectives and Progress

The objective of this project is to combine precision diffractive optical elements (DOEs) and micro-optic components with optoelectronic smart pixel (SP) chips to create dense, high-bandwidth optical interconnection channels, and to devise basic improvements in the accuracy and performance of DOEs by advanced design and fabrication. In these systems, the electronic processing is done with SP devices that combine arrays of light detectors, emitters or modulators, and electronics on a single substrate. The integration of smart pixels with diffractive and micro-optical components provides the internal interconnections and input/output interface. These systems realize parallel optoelectronic 2-D and 3-D communication, networking and computing systems having very high data throughput (10^{11} bits per second, or 0.1 Tb/s), very low latency ($< 10^{-8}$ s), and very high speed on each data channel (> 1 Gb/s).

In this project we have developed many new design methods for DOEs. DOEs are pure phase devices, so we derive algorithms to design DOEs phase elements that generate a specified power spectrum in the Fourier plane with very high precision. We apply a nonlinear least-square algorithm to design the DOEs that reconstruct a desired diffraction pattern with high uniformity, efficiency and signal-to-noise ratio. The technique also uses a phase-shifting quantization procedure that greatly reduces the quantization error for DOEs to a minimum level. The simulated reconstruction results of DOEs by use of these methods are much more accurate than the results obtained by the commonly used two-stage iterative Fourier transform design algorithm.

We have designed, fabricated and tested nine different diffractive microlens arrays for spot array generation based on the hybrid phase level method described previously. Fabrication of these microlenses was provided by Honeywell's foundry service under the DARPA-sponsored CO-OP foundry run. Contact lithography and reactive ion beam etching were employed to micromachine the phase profile into the substrate. The substrate material of these microlenses is fused silica with refractive index of 1.4525 and thickness of 500 μm. The binary micromachining fabrication method was applied that uses three masks, or etch steps, to provide a staircase phase profile maximum of eight phase levels. The fabrication minimum linewidth is restricted to be 1.5 μm and resolution is 0.05 μm The designed operation wavelength is 850 nm, and the active area is 1×1 mm². The designs included nine different 10×20 diffractive microlens arrays with hybrid phase levels that achieve a N.A. up to 0.3 using an 8 phase level fabrication process at minimum linewidth of 1.5 μm. Each lenslet has a rectangular aperture of size 62.5 μm × 62.5 μm or 125 μm × 62.5 μm with a focal length ranging from 312 μm to 3 mm. These microlens arrays use hybrid phase levels of 4/8 or 2/4/8 and the diffraction efficiencies are improved. The microlens arrays are used in a free space optically interconnected smart pixel system.

We also developed several new design methods for diffractive microlenses. It is well known that the diffraction efficiency of diffractive microlenses increases with the number of fabrication phase levels. In addition, the maximum numerical aperture (N.A.) of these lenses is inversely proportional to the product of the number of phase levels and the finite fabrication linewidth. Thus, to achieve a higher N.A., a design with fewer phase levels can be used at the sacrifice of diffraction efficiency for a given fabrication linewidth. The degradation of diffraction efficiency is most significant for microlenses having a small number of phase levels (e.g. 2 through 4). We have described a novel design for diffractive microlens arrays that uses a spatially varying hybrid number of phase levels to improve the diffraction efficiency at higher N.A. We analyzed the hybrid phase level diffractive lenslet design and showed the relation among the combined hybrid diffraction efficiency, N.A., and

number of hybrid phase levels. We discussed both the simple two hybrid phase level cases and generalized multiple phase level cases. Based on our analysis and simulation, for the case of two hybrid phase levels, the efficiency of a binary phase microlens is optimized when the inner zones are replaced with 3 phase level quantization and the efficiency is improved from 0.40 to 0.53. The efficiency of a four phase level microlens is optimized when the inner zones are replaced with 6 phase level quantization and the efficiency is improved from 0.81 to 0.85. In the generalized multiple hybrid phase level cases, the efficiency of a binary phase microlens reaches 0.58 and the efficiency of a four phase level microlens improves over 0.88. Our method pushes the theoretical upper bond of standard diffractive microlens efficiency to higher levels.

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2. J.-F. Lin and A.A. Sawchuk, "Design of Diffractive Optical Elements with Optimization of Signal-to-Noise Ratio and Without a Dummy Area," *Applied Optics*, vol. 36, pp. 3155-3164, (1997).
3. C.-H. Chen and A.A. Sawchuk, "Nonlinear Least-Squares and Phase-Shifting Quantization Methods for Diffractive Optical Elements," *Applied Optics*, vol. 36, pp. 7297-7306, (1997).
4. J.-M. Wu, C.B. Kuznia, B. Hoanca, C.-H. Chen, L. Cheng, A.G. Weber and A.A. Sawchuk, "Smart Pixel ARray Cellular Logic (SPARCL) Processor for Eliminating SIMD I/O Bottlenecks: System Demonstration and Performance Scaling," in *Optics in Computing*, vol. 8, 1997 OSA Technical Digest Series, Optical Society of America, Washington, DC, 1997, pp. 152-154.
5. J.-M. Wu, C.B. Kuznia, B. Hoanca, C.-H. Chen, and A.A. Sawchuk, "Integration of CMOS/MQW Smart Pixel ARray Cellular Logic (SPARCL) Processors for SIMD Parallel Pipeline Processing," *Proc. 1997 North American Chinese Photonics Technology Conference (NACPTC 1997)*, Los Angeles, October 17-19 1997.
6. J.-M. Wu, C.B. Kuznia, C.-H. Chen, and A.A. Sawchuk, "Designs for Diffractive Microlens Arrays with Higher Numerical Aperture and Diffraction Efficiency," Optical Society of America Annual Meeting, Long Beach, CA, October 1997; OSA Annual Meeting Program 1997, *OSA Technical Digest Series* (Optical Society of America, Washington, DC, 1997), pp. 112.
7. A.A. Sawchuk, "Optoelectronic Memory Applications for VCSEL-Based Smart Pixels," *Proceedings, IEEE Lasers and Electro-Optics Society 1997 Annual Meeting*, San Francisco, November 10-13, 1997, pp. 149-150 (invited paper).
8. C.-H. Chen, B. Hoanca, C.B. Kuznia, A.A. Sawchuk and J.-M. Wu, "TRANslucent Smart Pixel ARray (TRANSPAR) Chips for High Throughput Networks and SIMD Signal Processing," *Proc. Fifth International Conference On Massively Parallel Processing Using Optical Interconnections (MPPOI'98)*, Las Vegas, June 15-17, 1998.
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Detection (CSMA/CD) Protocol," *Proc. IEEE Summer Topical Meeting on Smart Pixels*, Monterey, CA, pp. 51-52, July, 1998.
12. B. Hoanca and A.A. Sawchuk, "Cellular Interconnects Optimization Algorithm for Optoelectronic Single Instruction Multiple Data Arrays," *Applied Optics*, vol. 37, pp. 871-883, (1998).
13. A.A. Sawchuk, Optical Signal and Image Processing: From Analog Systems to Digital Pipeline Smart Pixels," *Proc. IEEE International Conference on Image Processing 1998*, (ICIP98), paper MP-00, Oct. 5-7, 1998, Chicago, IL (invited paper).
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15. J.-M. Wu, C.B. Kuznia, B, Hoanca, C.-H. Chen and A.A. Sawchuk, "Demonstration and Architectural Analysis of Complementary Metal-Oxide Semiconductor/Multiple-Quantum-Well Smart-Pixel Array Cellular Logic Processors for Single-Instruction-Multiple-Data Parallel-Pipeline Processing," *Applied Optics*, vol. 38, pp. 2270-2281, (1999).
16. C.B. Kuznia, J.-M. Wu, C.-H. Chen, B. Hoanca, L. Cheng, A.G. Weber and A.A. Sawchuk, "Two-Dimensional Parallel Pipeline Smart Pixel Array Cellular Logic (SPARCL) Processors: Chip Design and System Implementation," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 5, pp. 376-386, (1999).
17. C.-H. Chen, B. Hoanca, C.B. Kuznia, A.A. Sawchuk and J.-M. Wu, "TRANslucent Smart Pixel ARray (TRANSPAR) Chips for High Throughput Networks and SIMD Signal Processing," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 5, pp. 316-329, (1999), (invited paper).
18. C.B. Kuznia, C.-H. Chen, B. Hoanca, L. Zhang, D. Pansatiankul, J.-M. Wu, and A.A. Sawchuk, "Modular System Demonstrator for Hybrid VCSEL/MSM Smart Pixel Networking, OSA Topical Meeting on Optics in Computing, April 12-16, 1999, Snowmass Village, CO., *1999 OSA Technical Digest Series*, Optical Society of America, Washington, DC.
19. C.-H. Chen, J.-M. Wu, B. Hoanca, D. Pansatiankul, L. Zhang, C.B. Kuznia, and A.A. Sawchuk, "High Throughput Networking and Signal Processing Using Modulator and VCSEL-MSM Based Smart Pixels," *Proc. 1998 International Photonics Conference (IPC '98)*, pp. 449-451, Taipei, Taiwan, R.O.C., December 1998.
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21. A.A. Sawchuk, "Digital Optical Computing and Networking with Smart Pixels," U.S.-Japan Joint Optoelectronics Project (JOP) Fifth Expert Workshop, San Diego CA, July 30, 1999.
22. C.B. Kuznia, C.-H. Chen, B. Hoanca, D. Pansatiankul, L. Zhang and A.A. Sawchuk, "Parallel Pipeline Networking and Signal Processing with VCSEL-MSM Smart Pixels," Optical Society of America Annual Meeting, Santa Clara, CA, September 1999; *OSA Annual Meeting Program 1999,* (Optical Society of America, Washington, DC, 1999), pp. 80.

Graduated Ph.D. Students

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"Ultra-High-Capacity Optical Switching"

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OE-5

I. RESEARCH REPORT

Two basic problems exist in a data-intensive dynamic battlefield theater-of-operations requiring high-capacity switching, these being: (i) high-speed bursty data traffic, and (ii) traffic originating from and routed to different geographic locations. We want to perform the required switching and routing all-optically to minimize: (a) the speed bottleneck, and (b) eavesdropping/jamming. High-bandwidth switching and selective routing can provide dramatically higher capacity and functionality. When transferring secure and bursty data between the front and support lines, there will be a necessity to reconfigure the network connections. Such switching can accommodate fiber and non-fiber systems and act as a gateway between a military network and the wider communications grid. During the past three years we have worked on the following projects with the funds received from Joint Services Electronics Program.

I.a. We have investigated novel ultra-high-capacity switching of signals in a nonlinear optical loop mirror (NOLM) since the NOLM has the capacity to switch at much higher speeds than other methods. We increased switching capacity and functionality by coupling an NOLM with a wavelength-dependent switch for ***simultaneous time and wavelength switching***. We explored the fundamental scientific issues which may limit the performance of such an ultra-high-speed switching system of ~100 Gbit/s on each of several different wavelengths, potentially enabling a **Tbit/s switch** Some basic and fundamental scientific issues have included: control of nonlinearities for enhancing the extinction ratio, optimizing the use of a rapidly-tunable parametric amplifier, examining the walk-off among wavelengths in the dispersive loop, and probing the limits of time and wavelength tuning speeds and channel spacings.

I.b. We have demonstrated all-optical wavelength-independent header replacement at 1-Gb/s without using a CW tag that precedes the packet. The new header is created by optically modulating a CW region generated from the data packet's own flag, thereby ensuring that the new header is at exactly the same wavelength as the original packet. This CW region, which can be tuned to any length within bandwidth of EDFA, is produced by replicating the packet flag several times in a recirculating fiber loop. A power penalty of ~1.5 dB at a BER=10^{-9} is measured when performing the header replacement. Although generating the CW tag locally adds certain complexity, the generic SONET/ATM packet structure is maintained in this approach.

I.c. We have reported: (i) the fabrication and tuning characteristics of a novel *nonlinearly-chirped* fiber Bragg grating in which a *single* piezoelectric transducer is used to tune the dispersion, and (ii) the first system demonstration of dynamic dispersion compensation for a 10-Gb/s optical channel. The time delay induced by this nonlinearly-chirped fiber Bragg grating

changes with wavelength in a nonlinear fashion. We tune the resonant wavelength of the fiber Bragg grating and change the generated dispersion continuously from 300 to 1000 ps/nm for a given channel. In our system demonstration, a phase modulation to amplitude modulation (PM-to-AM) technique is used to dynamically determine the relative accumulated dispersion in a channel. This PM-to-AM signal drives the piezoelectric transducer to induce the appropriate amount of inverse dispersion necessary for compensation. By switching between two different lengths of single-mode fiber (SMF), the power penalty is reduced to <1 dB both for a link containing high dispersion (104 km, initial penalty = 3.5 dB) and for one containing low dispersion (50 km, initial penalty = 1.5 dB). Compensation is achieved in less than 2 ms, which is appropriate for circuit-switched networks.

I.d. For efficient and high-throughput switching of optical data packets, header bits in each packet must be decoded and acted upon quickly. In this work, we have demonstrated all-optical recognition of the header information in a data packet as well as routing of packets through an optical switch based on the decoded information. Our technique is tunable and can recognize different packet headers in a reconfigurable network. The operation is accomplished by shifting each bit of a header packet onto a different wavelength, introducing different time delays for each wavelength, and then using an optical decoder to determine if the series of header bits match the header code of a tunable optically-encoded look-up table. We have used time-to-wavelength mapping and an array of fiber Bragg gratings to detect the correct header. We have achieved penalty-free routing with a 1.6-ns guard time.

I.e. Resolving output-port contention, in which two data packets located at the same wavelength and at two different input ports request to be routed to the same output port, enables all data packets out their desired ports without incurring additional latency. We have demonstrated **all-optical** contention resolution for two identical-wavelength contending incoming 2.5 Gbit/s channels by optically up-converting one channel to a higher microwave frequency beyond the other channel's baseband signal and routing both channels out the desired output-port wavelength channel simultaneously. By using narrow (~5 GHz) fiber Fabry-Perot filters for optically demultiplexing the two channels, we recover each channel using a baseband receiver with <1 dB power penalty.

II. GRADUATED STUDENTSwho received support from JSEP program:

1. Imran Hayee
2. kai-Ming Feng
3. Jin-Xing Cai

III. BIBLIOGRAPHY (A.EWillner publications supported by the JSEP program)

III.a. Refereed Journals:

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4. A.E. Willner, "Dynamic WDM Optical Systems and Networks," **Invited Paper, International Conference on Applications of Photonic Technology**, Ottawa, Canada, July 1998.

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